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Tunable Liquid Crystal – Photonic Crystal Fiber Interferometer

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ABSTRACT:

In this work, we present a novel interferometer based on liquid crystal and photonic crystal fiber technology. The objective of this project is the development of a tunable (switchable) modal (Mach-Zehnder) interferometer for optical communications or sensing.

Key words: Mach-Zehnder interferometer, liquid crystal, photonic crystal fiber, polarization maintaining fiber, tunable interferometer.

1.- Introduction

Photonic Crystal Fibers (PCFs) are micro-structured fibers with periodically distributed air holes in the cladding region. These air holes can be infiltrated with liquid or gases. PCFs may feature solid core guiding by modified Total Internal Reflection (mTIR) or hollow core, whose guiding mechanism is by Photonic Band-Gap (PBG) transmitting only certain wavelengths values [1]. Some sorts of PCFs have several cores or holes of different diameters in order to improve specific properties as endlessly modes or polarization maintaining. These properties may be further boost by infiltrating in the holes a birefringent medium such a liquid crystal.

In this work, a Polarization Maintaining PCF (PM-1550) of NKT Photonics has been employed. This fiber shows two opposite wider holes around the non-circular core that creates strong birefringence (Fig.1).

Taking advantage of the differences in the hole diameters it has been possible to collapse and filling selectively either the wider or the narrower holes with liquid crystals (LC). This opens the possibility of creating fiber-based tunable interferometers.

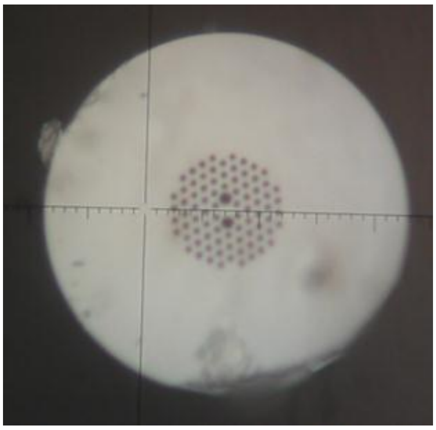

Fig. 1: PM-1550 manufactured by NKT Photonics.

2.- Mach-Zehnder Interferometer (MZI)

By introducing collapsed regions or offset splicing at the splicing points of a PCF and two single-mode fibers (SMFs), one can create a Mach-Zehnder Interferometer (MZI). Both the core mode and cladding mode can be simultaneously induced at one splicing point, propagating along different optical paths. The modes are recombined at the second splicing point, and interference patterns can arise at the output (Fig. 2). Previous studies have demonstrated that liquid-filled PCF MZIs can be successfully utilized in applications of sensing for bending and refractive index [2].

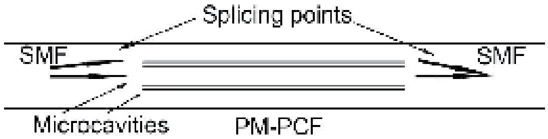

Fig. 2: Scheme of a MZI-PCF

Actually the liquid crystal need not be infiltrated into the microchannels to produce tunable effects. PCFs are very sensitive to their environment; Therefore a switchable PCF-MZI device may be developed merely surrounding the fiber MZI externally with the liquid crystal. In this way, standard LC cells have been prepared using ITO-coated glasses and SMFs as spacers. The LC molecular director can be reoriented by an electric field applied between the two glass plates. Initially the LC is aligned homogeneously. After applying a sufficiently high electric field, the alignment switches to homeotropic.

The selected PCF works on a two-LP-mode operation. When LP light is launched at 45º relatively to the eigenaxes of the high birefringent PCF, both polarization states of the two spatial modes LP_{01}(xy) and LP_{11}(xy) are simultaneously excited, generating a multibeam interference [3].

3.- Fabrication process

3.1.- Fusion splicing

The splicing points of the interferometer are critical because the cladding mode is induced or recombined within these regions. The fusion process has been realized using an Ericcson Fusion Splicer FSU-900.

Two separate splicing processes had to be developed. The fusion of an empty PCF with a SMF to induce cladding modes requires to fully collapse the intermediate region. If the PCF is totally or selectively filled with a LC, the fusion process must be made with extreme care to avoid LC decomposition. In this case the current intensity must be much lower; otherwise bubbles are formed inside the fusion region.

Alignment is also important in both cases, because it determines the power balance between the two paths of the interferometer (Fig. 3).

In the case of MZIs with externally surrounded LC, both splicing points were completely collapsed.

Fig. 3: PCF selectively filled with LC fusioned superficially with SMF (top) and PCF-SMF totally collapsed fusion (bottom).

3.2.- Liquid Crystal encapsulation

The interferometer has been encapsulated between two ITO-coated glasses using SMFs as spacers. In this way, an electric field across the fibers may be applied by applying voltage to the ITO electrodes. Both glasses have been preconditioned to anchor the LC molecules parallel to the surface in absence of an electric field. When a field is applied to the cell, the LC molecules will reorient to become parallel to the field (i.e., perpendicular to the glasses). Upon reorientation the LC intends to reach a minimum energy state that depends on the field strength and the anchoring force that try to keep the molecules parallel to the substrates. This reorientation can be therefore modulated, making it possible to modify the effective refractive index 'seen' by the evanescent field of the propagating light waves.

The alignment of LC molecules in infiltrated PCF is more complex. Alignment preconditioning of the inner microchannel surfaces inside the fiber proved to be unfeasible. Alignment is achieved by taking advantage of the LC viscous anisotropy, by which a LC flowing in a capillary spontaneously orients along the flow direction. Therefore molecules become homogeneously oriented, parallel to the walls of the cavity. When an electric field is applied, molecules tend to align orthogonally to the walls, parallel to the electric field lines (Fig. 4).

Homeotropic alignment (i.e., perpendicular to the walls) has been tried as well, with the added difficulties mentioned above. Although homeotropic alignment could be attractive for a number of applications, the outcome is quite involved in practice. Indeed, homeotropic conditioning of the microchannel walls does not lead to a symmetric radial structure but rather to an escaped radial structure, with a third dimension escape, whereby the energetically disfavored molecular interactions at the center of the capillary are avoided. Even in the ideal case the third dimension escape is rarely a homogenous structure since there are two degenerate opposite escape directions, giving rise to domain formation and scattering.

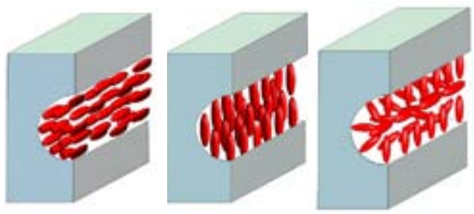

Fig. 4: Homogeneous alignment of LC molecules (left), perpendicular aligment with applied electric field (center) and radial third-dimension escape (right).

It's difficult to observe the alignment of the LC molecules inside a specific cavity of the fiber through the microscope because of the scattering of the whole cladding.

The used method has been to focus on the collapsed region of the spliced point where it is possible to see the two wider cavities that are not collapsed yet. Using crossed polarizers it's possible to observe the LC alignment by changing the orientation of the fiber from parallel to 45º respect to the polarizer (Fig.5).

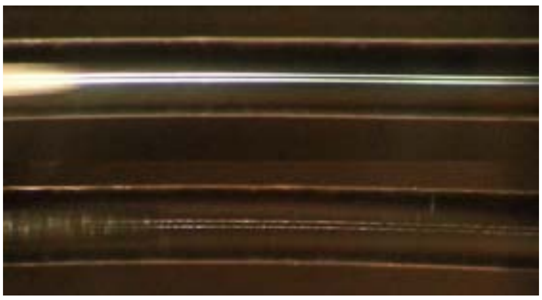

Fig. 5: PM-PCF with his wider cavities filled with MLC-1300 between polarizers at 45º to one (top) and parallel (bottom).

4.- Characterization

4.1.- MZI surrounded by LC

Two tunable lasers in the 1450-1550 nm and 1510-1650 nm bands have been used for measurements and characterization. Lasers show a wavelength-dependent elliptical quasi-linear polarization. The polarization of the impinging light had to be controlled and monitored in order to maintain it constant throughout the whole measurement.

Several MZIs with different lengths were fabricated in order to observe the dependence between the MZI length and the period of the pattern. It turns out that the period is inversely proportional to the length as shown in Fig. 6.

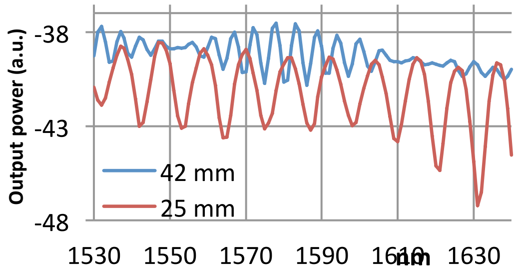

Fig. 6: Dependence of fringe spacing with MZI length.

The period or fringe spacing $\Delta\lambda$ of these interferometers is

$$\Delta\lambda \approx \frac{\lambda^2}{\Delta n_{eff} L} \qquad [1]$$

being Δn_{eff} the effective refractive index difference between the modes participating in the interference [4].

In the measurement of the MZI surrounded by LC a circular polarization was set due to his wavelength independence inducing a multibeam interference. The two sets of interference patterns, corresponding to two orthogonal polarizations, are superimposed, resulting in an amplitude-modulated wave (Fig. 7).

It is easy to see how the amplitude increases in the higher-amplitude zone when voltage is applied and how the phase changes in the lower-amplitude zone. In fact this change in phase only is showed in the lower-amplitudes zones while no change is visible in the higher.

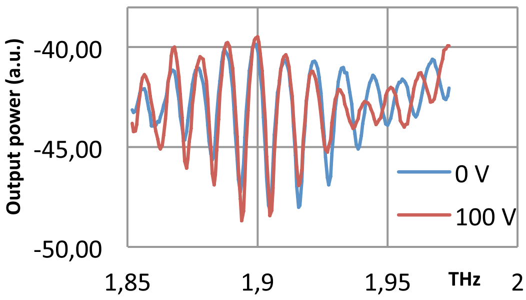

Fig. 7: Interference pattern of a Mach-Zehnder Interferometer of 42mm surrounded by MLC-13000 LC

Applying Fast Fourier Transform it is possible to obtain the relationship between the frequency of the spectrum fringes and their amplitudes. The two set of peaks showed in Fig. 8 represent the two-LP-mode interferometer between LP_{01}(xy) and LP_{11}(xy).

The amplitude changes with the orientation of the input polarization. Each peak represents the interferometry of modes of the same x or y axis.

4.2.- MZI with LC in his wider microcavities

In the interferometer filled selectively with LC, the variation of the pattern when an electric field is applied is much more abrupt, although the interference pattern is not as clear as the previous one. The setup is much more sensible to the polarization. A band-gap is detected for certain voltage values as the axis along the cavities filled with LC is guided by PBG rather than mTIR like the orthogonal axis.

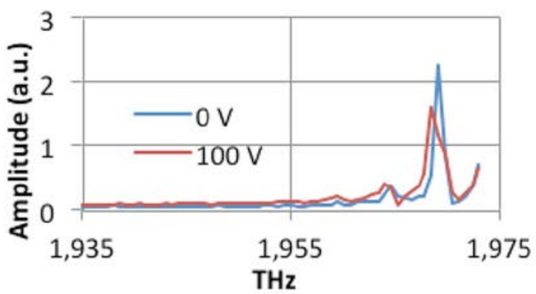

Fig. 8: FFT of the interferometer with and without applied electric field.

Measurements were taken on the same setup using circular polarized light (Fig. 9) and linear polarized light afterwards (Fig. 10).

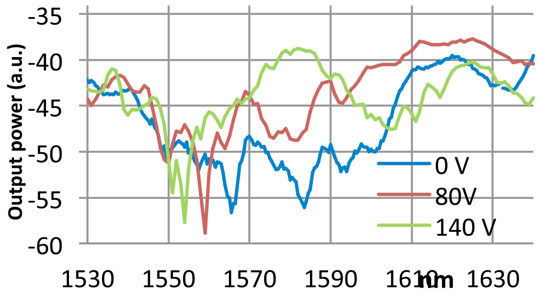

Fig. 9: MZI of 16 mm filled with LC selectively at various applied electric fields launched with circular polarized light.

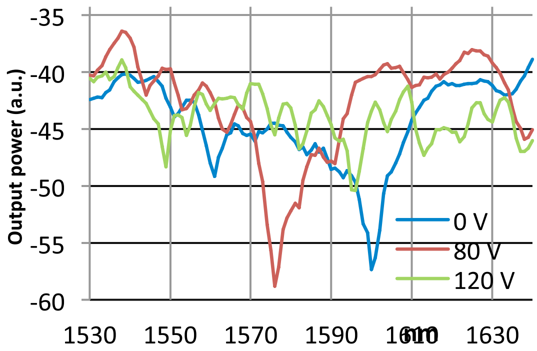

Fig. 10: MZI of 16mm filled with LC selectively at various applied electric fields launched with circular polarized light.

A band-gap is observed in the absence of electric field (@ 1600nm, see Fig. 10). The band-gap performs a hypsochromic shift (about 25nm) when an 80 V voltage is applied; while disappears when voltage is rised up to 120V.

5.- Conclusions

In this study the possibility of manufacturing a tunable Photonic Liquid Crystal Mach-Zehnder Interferometer has been demonstrated. The MZI is sensible to polarization and voltage controllable.

MZIs for different applications based on the same design can be prepared by changing several properties as the MZI length, the type of PCF or Micro Structured Fiber and the type of Liquid Crystal. If third-dimension escape of homeotropic samples could be effectively controlled, this orientation associated to negative electric anisotropy LCs would be interesting for inducing polarization-insensitive axial symmetric LC reorientations.

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